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ABSTRACT

One effect of using pressure sensitive paint (PSP) is the potential intrusiveness to the aerodynamic characteristics of the model. The paint thickness and roughness may affect the pressure distribution, and therefore, the forces and moments on the wind tunnel model. A study of these potential intrusive effects was carried out at NASA Langley Research Center where a series of wind tunnel tests were conducted using the Modern Design of Experiments (MDOE) test approach. The PSP effects on the integrated forces were measured on two different models at different test conditions in both the Low Turbulence Pressure Tunnel (LTPT) and the Unitary Plan Wind Tunnel (UPWT) at Langley. The paint effect was found to be very small over a range of Reynolds numbers, Mach numbers and angles of attack. This is due to the very low surface roughness of the painted surface. The surface roughness, after applying the NASA Langley developed PSP, was lower than that of the clean wing. However, the PSP coating had a localized effects on the pressure taps, which leads to an appreciable decrease in the pressure tap reading.

NOMENCLATURE

A& B	Stern-Volmer Coefficients
C_d	Coefficient of drag
C_l	Coefficient of lift
C_p	Pressure Coefficient
DQA	Data Quality Assurance
K	Stern-Volmer constant
M	Mach Number
MDOE	Modern Design of Experiments
OFAT	One-Factor-at-a-Time
Re	Reynolds Number
α	Angle of attack, deg
P_1	Reference Pressure
P_2	Measured pressure

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INTRODUCTION

The PSP measurement technique is used to measure the global pressure distribution on wind-tunnel models by painting the article surface with a luminescent paint. When the paint is illuminated by light of appropriate energy, the emitted intensity is inversely proportional to the pressure. The pressure distribution can be obtained from the intensity distribution of the PSP. Details of the theory and applications of PSP can be found in the literature [1-4].

Although the PSP technique is becoming an alternative to the classical method of measuring pressure through taps, there are still aspects of the method that need to be improved. One aspect that has not been fully characterized is the possible intrusive effect of the PSP on the aerodynamic flow over a test model. The paint affects the test article surface finish, thickness, and shape. Paint intrusiveness may not directly affect the pressure-measurement, but the surface finish can have an effect on the boundary layer, skin friction, shock location, and drag.

Several studies [5,6] have shown that the paint can cause a displacement of the shock wave slightly upstream from where it would occur on a clean wing at transonic cruise condition and for a high lift wing. Also, the stall angle decreases slightly when PSP is applied. Vanhoutte's experiments [7] showed up to 50 drag counts are possible for a rough PSP surface finish and the thickness of the paint layer may interfere with transonic band at high subsonic speed. Meborki's work showed that PSP could cause reduction in lift at high angles of attack with smooth and thin PSP layers at high Reynolds numbers [8].

This paper describes the results of a research program focused on characterization and quantification of the

intrusive effects of PSP. The paper provides a detailed description of three wind tunnel tests that were conducted to study the paint effects. A Modern Design of Experiments approach was used to increase confidence in the results by properly matching data volume to precision requirements of the test [13].

METHODOLOGY

Wind Tunnel

The Langley Low-Turbulence Pressure Tunnel (LTPT) is a single-return, closed-circuit tunnel that can be operated at stagnation pressures from 0.1 to 10 atmospheres. LTPT is a unique facility that provides flight Reynolds number tests capability for two-dimensional airfoils and a low turbulence environment for laminar flow control studies. The 65° delta wing was tested at LTPT at Mach 0.20, a Reynolds number range of 4-13 million per foot and an angle of attack range of -2 to 14 degrees.

The Langley Unitary Plan Wind Tunnel (UPWT) is a closed-circuit pressure tunnel with a test section that is 4 feet by 4 feet in cross section and 7 feet long. The Mach number range is approximately 2.30 to 4.63. The slender arrow wing -fuselage-nacelle model was tested in UPWT at Mach 2.4, Reynolds number of 4 millions per foot, and an angle of attack of -2 to 6 degree.

Model

The 65° Delta wing model, constructed of stainless steel, had an NACA 64A005 airfoil section from the 40-percent chord station to the wing trailing edge. The right wing was instrumented with 54 pressure taps placed in three chord wise rows on the upper surface. The model was instrumented with a force and moment balance. Figure 1 shows the model schematic and target locations.

A 1.675%- scale Arrow Wing model was tested to determine the effect of pressure-sensitive paint (PSP) on the longitudinal force and moment characteristics of a slender wing-fuselage configuration at supersonic speeds. Figure 2 shows the slender narrow wing-fuselage-nacelle model. Model length was 52.74 inches, model span was 25.794 inches, and model height was 5.00 inches. This model was not instrumented with any surface static pressure taps.

PSP Paint

The PSP system used for all tests consisted of a white primer and a PSP topcoat. The primer was a two part commercial automotive primer. The models were thoroughly cleaned before a spray application of the primer. The primer was cured until it was hard enough to sand and resist attack by paint solvents. The primer was wet sanded with 1000 grit paper until the entire surface had a dull finish. The surface was then wiped with tetrahydrofuran (THF), which served to prime the surface for better adhesion of the PSP to the white primer. The PSP was then applied by spraying. The PSP was composed of poly-tifluoroethylmethacrylate-co-isobutylmethacrylate (FEM) as the binder, lacquer thinner solvents, and platinum tetra (pentafluorophenyl) porphyrin (PTP). Sufficient PSP was applied to give a uniform, medium shade of pink. The constants for a linear calibration plot of I_{ref}/I vs P/P_{ref} were A = 0.172, B = 0.828.

The instrument used to measure the thickness of the primer and PSP coating was a DualScope MP4 by Fischer. The instrument utilized the eddy current test method.

Surface roughness was measured using a Mitutoyo Surftest-211. The instrument measurement range was 0.05 – 40 μm (2- 1600 μin). The instrument was set-up to read the average peak height of the roughness over the measured distance.

Modern Design of Experiment

Modern Design of Experiments (MDOE) is a testing method used to improve the data quality while relaxing the requirements for high-volume data collection [references 9,10,11]. Conventional One-Factor-at-a-Time (OFAT) testing is conducted by holding all variables constant while sequentially changing a single independent variable. The OFAT approach is prone to superposition of systematic errors that might occur as a result of drifts in the tunnel operating condition. MDOE features the processes of blocking, randomization, and replication to increase the quality of data obtained in wind tunnel testing. Blocking effects can be used when the response variables such as the balance forces and moment measured in one specific block of time differ from measurements made in another block of time under specific conditions that should give a similar results.

Two tests at two different wind tunnels used the MDOE technique to identify intrusive aerodynamic

effect caused by PSP. The independent variables were angle of attack and paint state (on/off), while the response variables were the balance six-components of forces and moments. As part of the MDOE process, several issues were addressed during the design of the experiment, such as the resolution level of parameters to be measured, randomization of PSP application, the tunnel control system, and inference error risk of the results. The design was developed to be a split plot-design with orthogonal blocking. Table 1 shows an example of the completed test matrix in the UPWT test using MDOE.

RESULTS

Low Speed Testing at LTPT

A low speed force and moment test was conducted using the 65° delta wing in the LTPT facility. The objective of this test was to characterize the effect of PSP on drag and lift coefficients. The MDOE pre-test analysis suggested that five paint applications would be needed to quantify the effect of the paint with a desired precision level. This method was time-consuming because eight hours was required to apply and cure the paint. However, each application represented only one degree of freedom to describe the effect of a change in paint state (paint on to paint off). Multiple paint-state changes were required in order to produce enough degrees of freedom to quantify both the main paint-state effect and the uncertainty in estimating that effect. Figure 3A shows the thickness of the five different paint jobs at different times. Figure 3B shows the corresponding roughness of each paint application. Notice from this figure that the average thickness for the paint was 2.5 mils and the average roughness was 7_{μ}-in. The test conditions were Mach 0.20, Re from 4 to 13 million, and angle of attack from –2 to 14 deg. The data was acquired at constant Mach and variation of Re and AOA for five repeated paint applications. For each paint application, there were five replicates data sets. Therefore, for each AOA position obtained a total of 25 data points were processed and analyzed. Figure 4 shows the drag coefficient vs. lift coefficient for both painted wing and clean wing for Mach 0.2 and Re of 13 million for five replicates. It was difficult to differentiate the paint and clean wing data for this condition. It appears that the PSP had no significant effect. To verify that, a closer look at the data was necessary. The calculated differences of C_d for painted and clean wing as a function of AOA at different Re numbers were plotted as shown in figure 5. Moreover, the standard deviation for each measurement was displayed. It was reasonable to conclude that the PSP had no effect on the coefficient of drag. Similar results were obtained for coefficient of lift and all the moment components.

A surface pressure test was conducted at LTPT on the same 65° delta wing model to continue the characterization of the PSP on pressure distribution. This test was under a time constraint from the facility and the issue of multiple-paint applications had to be resolved. It was decided that for this test, one paint application would be used to acquire all the necessary data. The test conditions for this entry were M at 0.20-0.34, Re at 4- 13 millions, and AOA from –2 to 25 deg. Figure 6 A and 6B show the thickness and roughness of this paint application. By adding the PSP to the model, it was noticed that there was a reduction in C_p tap values for all three rows of taps. Figure 7A thru 7D displays C_p as a function of AOA at Mach of 0.25 and Re of 10 millions for a specified pressure tap from each row on the model (R1T2= row 1 tap 2.) Figure 8 shows the delta C_p between painted and clean wing vs. AOA at Mach of 0.25 and Re of 5M/ft.

Apparently paint around the taps influences the behavior of the flow around the taps. A study was carried out to obtain the image of close-up of the taps. Figure 9 shows an example of the profiles of the taps with PSP applied; tap A was clean tap J was half clogged, and there was a great deal of paint irregularities around that tap. These results displayed were unexpected trends because the integrated force and moment data did not show a paint effect in the earlier tests. The reduction in C_p may be due to the localized effect of the paint, but when the integrated force was calculated over the painted surface, the effect was insignificant. Painting a model with PSP is an art that requires certain skills, so that the paint application will not influence the aerodynamic results.

An accurate static surface pressure distribution is particularly important for the PSP technique because the PSP image processing requires an in-situ calibration. If the pressure tap values are affected by the paint, uncertainties in the calculated C_p from the PSP images will increase. Further tests are necessary to evaluate this effect; a scheduled test at UPWT facility is planned in 2001 to address this issue.

Supersonic Testing at UPWT

The slender arrow wing-fuselage model was tested at Mach number and Reynolds number were fixed at 2.4 and 4.0 million per foot, respectively. The angle of attack was -2 to +6 degrees. This test was a force

and moment test and no PSP image was taken. The PSP was applied four times and MDOE was used to acquire all the necessary data. The independent variables were angle of attack and paint state (on/off), while the response variables were the balance six-component forces and moments. Moreover, repeat runs were taken at the beginning and end of the test entry. These runs were part of the Data Quality Assurance (DQA) program at LaRC. The PSP was applied to a wing featuring existing transition trip dots near the leading edge. This created difficulties in stripping and reapplying the PSP. Several alternatives were evaluated, such as applying the paint over the trip dots, but this affected the local geometry of the dots and their ability to promote boundary layer transition. Another alternative was to apply the trip dots over the PSP, but adherence properties of the dots to the PSP were poor. Finally, the trip dots were applied over the base coat in a narrow strip along the leading edge. The change time increased due to reapplying the trip dots after each paint state. The paint thickness and roughness were measured after each paint applications (see figure 10.) This solution was proved to be satisfactory.

The results shown in figure 11 were based on four replicates on the model with paint-on and -off the wings indicating that the paint effect on the drag coefficient is not resolvable. The effect is not distinguishable from zero within the 95% confidence level. Figures 12 and 13 show that the paint effect is within the tunnel variations for C_d and C_l. Figure 14 shows the result of the three repeat runs for the DQA program and indicates the same result as the MDOE method. The paint has no measurable effect. Thus, we could combine force and moments tests with pressure tests, if the PSP can be accurately calibrated.

Analysis of the data indicates that the scatter in the normal force, axial force, and pitch moment coefficients in the attached flow regime were typically +/-0.01, +/- 0.00005, and +/- 0.0001, respectively. Figures 15 shows an example of the processed results for pitch moment.

ANALYSIS

A thin PSP coating can modify slightly the overall shape of a model and produce local surface roughness and topological patterns. These unwanted changes in model geometry may alter the flow over the model and affect the integrated aerodynamic forces. Aerodynamic mechanism of PSP intrusiveness will be briefly discussed here and some observed results will be reviewed. Basically, the effects of a PSP coating on pressure and skin friction are directly associated with local changes of flow structures and propagation of the perturbations in the flow. The changes in the integrated aerodynamic forces are mainly induced by these local changes.

Effects on Pressure

In order to clarify the effects of a PSP coating on pressure, we have to consider different flow scenarios.

(1) Attached flows

When flow over a simple aerodynamic model is attached, a quantity to characterize the effect of a PSP coating is a ratio between the boundary-layer displacement thickness δ_l and the local paint thickness variation Δh. For $\delta_l / \Delta h >> 1$, the external inviscid flow is not altered by the PSP coating. This is a condition under which PSP measurements are normally conducted. However, when the Reynolds number is so large that $\delta_l / \Delta h \sim 1$, a PSP coating may directly change the external inviscid flow, particularly near the leading edge of the model.

Instead of directly altering the outer flow, a rough coating may indirectly result in a local pressure change by thickening a boundary-layer. Roughness of a coating, which is considered as a spatially random thickness variation Δh with a short wavelength, increases the displacement thickness δ_l by either triggering laminar-turbulent transition or reducing the momentum of the turbulent boundary-layer. Thus, the effective shape of the model is changed and the pressure distribution on the model is modified. This effect is most significant near the trailing edge due to the development of the boundary-layer. Vanhoutte et al. [7] have observed the increments in trailing edge pressure coefficient relative to the unpainted model, which is consistent with an increase in the boundary-layer thickness in the trailing edge.

A bad coating may form local topological structure around a pressure tap (see Fig. 9). The local protuberance near the tap may change the pressure readings from the tap. The reduction of the pressure readings from taps have been found in our tests, as shown in Fig. 7. This may give false indications of paint intrusiveness since this phenomenon is localized. This may lead to an error in in-situ PSP calibration in which pressure tap data are used as standard values.

A coating adds additional thickness h to the model geometry and slightly enlarges the model scale. When the thickness is much smaller than the characteristic length of the model, the paint thickness does not have a significant effect on the pressure distribution. For certain models such as a high-lift configuration, the paint may change the gap between a slat (or a flap) and the main wing when the gap is small. Thus, the pressure distribution on the model may be influenced.

(2) Separated flows and shock/boundary-layer interaction

A coating may influence laminar separation bubbles near the leading edge at low Reynolds number and high angle-of-attack. The perturbations induced by a rough coating near the leading edge may enhance mixing that entrains the high-momentum fluid from the outer flow into the separated region. Consequently, the coating causes the laminar separation bubbles to be suppressed. Vanhoutte et al. [7] have reported this effect and found a reduction in drag associated with it. The perturbations by a rough coating could be amplified by several hydrodynamic instability mechanisms such as the Kelvin-Helmholtz instability in the shear layer between the outer flow and separated region and the cross-flow instability near the attachment line on a swept wing.

Schairer et al. [5] observed that a rough coating on the slats slightly decreases the stall angle of a high-lift wing. He found that the empirical criteria of "hydraulically smooth" and "admissible roughness" based on 2D data are not sufficient to provide an explanation for the observation. Indeed, in 3D complex flows in the high-lift model, the effects of the coating on the cross-flow instability and interactions between boundary-layer and other shear layers, such as wakes and jets, are not fully understood at all.

Differences between the paint-off and paint-on data have indicated that a rough coating moves the shock wave slightly upstream (Schairer et al. [5]). The pressure distribution is shifted near the shock location. This change may be caused by interaction between the shock and the incoming boundary-layer affected by the coating. This effect is more closely associated with the historical development of the upstream boundary-layer influenced by the coating.

Effects on Skin Friction

Generally, surface roughness may be altered by a coating and skin friction may be changed when the roughness exceeds the admissible roughness (Schichting [12]). In attached flows at high Reynolds numbers, a rough coating increases skin friction by triggering premature transition in a laminar boundary-layer and increasing turbulent intensity in a turbulent boundary-layer. The increase in drag due to a rough coating has been observed in airfoil tests at high subsonic flows (Vanhoutte et al. [7]). Premature transition caused by a coating has been routinely seen in temperature sensitive paint experiments. In contrast, when a coating makes the surface smoother, skin friction drag is reduced. The reduction in drag by applying a smooth coating on the surface is clearly shown in Fig. 5. As mentioned before, a coating may influence flow separation by changing the separation line and attachment line. Thus, skin friction distribution is accordingly changed.

CONCLUSIONS

The PSP effects on the integrated aerodynamic forces on the two different models at different test conditions at both the LTPT and UPWT are very small over certain ranges of Reynolds number, Mach number and AOA. This is mainly because the tested PSP developed by NASA Langley produces surface roughness that is even smaller than the clean wing. In low-speed testing at LTPT, the differences of the coefficients of lift, drag and other components between the paint-on and clean models are within the error bounds of measurements by balances. However, an appreciable reduction of the pressure readings in some pressure taps was found on the paint-on model. This may be caused by local topological changes around the taps produced during the painting process. Although this localized effect on pressure taps does not significantly affect the integrated forces, it may lead to an error in in-situ PSP calibration when pressure tap data are used as standard values. Similarly, the supersonic speed testing at UPWT did not show any significant paint effects on the coefficients of lift, drag and other components.

ACKNOWLEDGMENT

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program. The authors would like to thank Clifford Obara and the Langley-PSP team members for the execution of the three wind tunnel tests in a short time frame. A special thank goes to Dick DeLoach, Modern Design of Experiment Expert, for using his method to develop the tests matrix for this research and to Gary Erickson, Bill Sewell, Frank Quinto, and their staff for the facility test support. We would also like to thank James Bell, NASA Ames, for his valuable discussions in the PSP application area.

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UPWT Test 1721 Arrow Wing Model Test Section 2				
Configuration	**Attitude**	**Runs**	**PSP**	**Run Description**
PSP patch w/ 2 rows of trip dots	A1	6,7,8	Patch	"Pre-test" shakedown runs for PSP/dot applications
Clean wing (baseline)	A2	11,12,13	Off	Baseline (unpainted) model runs (conventional polars)
Clean wing (baseline)	MDOE1	14	Off	Baseline (unpainted) model runs (MDOE runs), replicate 1
Clean wing (baseline)	MDOE2	15	Off	
Clean wing (baseline)	MDOE3	16	Off	
Clean wing (baseline)	MDOE4	17	Off	
Clean wing (baseline)	MDOE5	18	Off	
Painted RH wing	A2	30,31,32	On	Painted model runs (conventional polars)
Painted RH wing	MDOE1	33	On	Painted model runs (MDOE runs), replicate 1
Painted RH wing	MDOE2	34	On	
Painted RH wing	MDOE3	35	On	
Painted RH wing	MDOE4	36	On	
Painted RH wing	MDOE5	37	On	
Painted RH wing	MDOE1	40	On	Painted model runs (MDOE runs), replicate 2
Painted RH wing	MDOE2	41	On	
Painted RH wing	MDOE3	42	On	
Painted RH wing	MDOE4	43	On	
Painted RH wing	MDOE5	44	On	
Clean wing (baseline)	MDOE1	45	Off	Clean model runs (MDOE runs), replicate 2
Clean wing (baseline)	MDOE2	46	Off	
Clean wing (baseline)	MDOE3	47	Off	
Clean wing (baseline)	MDOE4	48	Off	
Clean wing (baseline)	MDOE4	49	Off	
Painted RH wing	MDOE1	51	On	Painted model runs (MDOE runs), replicate 3
Painted RH wing	MDOE2	52	On	
Painted RH wing	MDOE3	53	On	
Painted RH wing	MDOE4	54	On	
Painted RH wing	MDOE5	55	On	
Clean wing (baseline)	A2	65,66,67	Off	Clean model runs (conventional polars), replicate 3
Clean wing (baseline)	MDOE1	68	Off	Clean model runs (MDOE runs), replicate 3
Clean wing (baseline)	MDOE2	69	Off	
Clean wing (baseline)	MDOE3	70	Off	
Clean wing (baseline)	MDOE4	71	Off	
Clean wing (baseline)	MDOE4	72	Off	
Painted RH wing	A2	83,84,85	On	Painted model runs (conventional polars)
Painted RH wing	MDOE1	86	On	Painted model runs (MDOE runs), replicate 4
Painted RH wing	MDOE2	87	On	
Painted RH wing	MDOE3	88	On	
Painted RH wing	MDOE4	89	On	
Painted RH wing	MDOE5	90	On	
Clean wing (baseline)	A2	92,93,94	Off	Clean model runs (conventional polars), replicate 4
Clean wing (baseline)	MDOE1	95	Off	Clean model runs (MDOE runs), replicate 4
Clean wing (baseline)	MDOE2	96	Off	
Clean wing (baseline)	MDOE3	97	Off	
Clean wing (baseline)	MDOE4	98	Off	
Clean wing (baseline)	MDOE4	99	Off	

Table 1. MDOE Summary of the Test Run Matrix

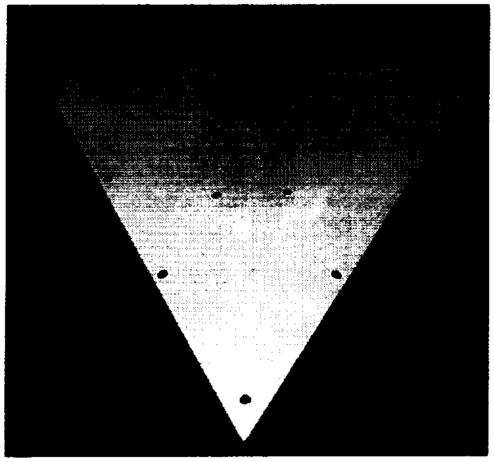


Figure 1. 65° Delta Wing Model Painted with PSP and Marked with Target Points at LTPT

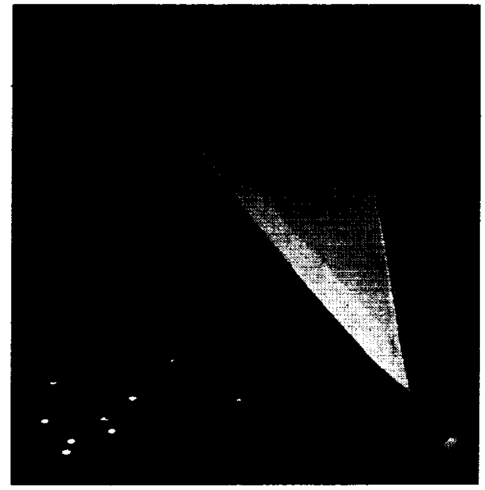
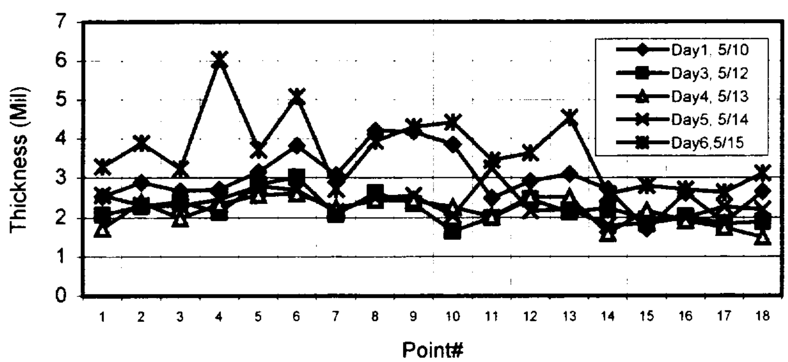
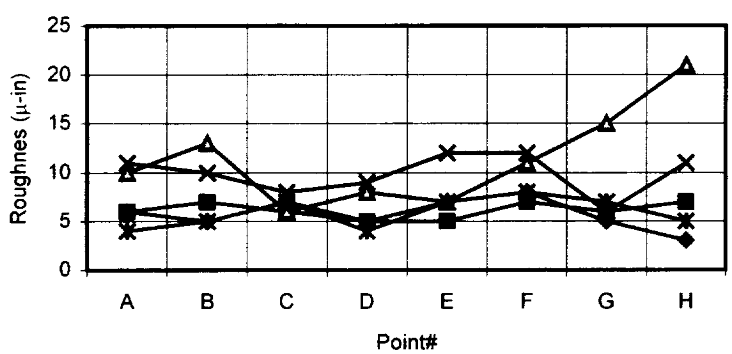


Figure 2. Arrow Wing Model Painted with PSP and Trip Dot at UPWT



(A)



(B)

Figure 3. Thickness and Roughness Variations of Painted Model

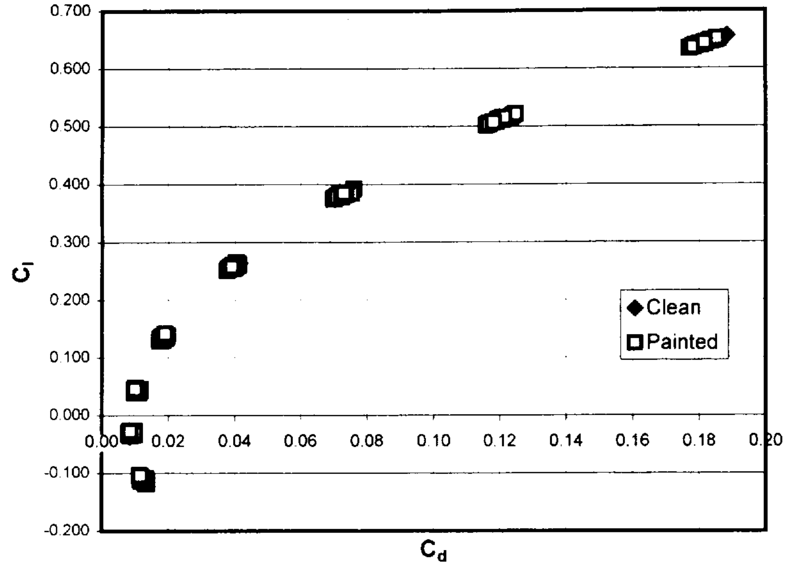


Figure 4. The difference in C_l Vs. C_d of Painted and Clean Wing at LTPT for Mach= 0.20, Reynolds=13M for Five Replicates

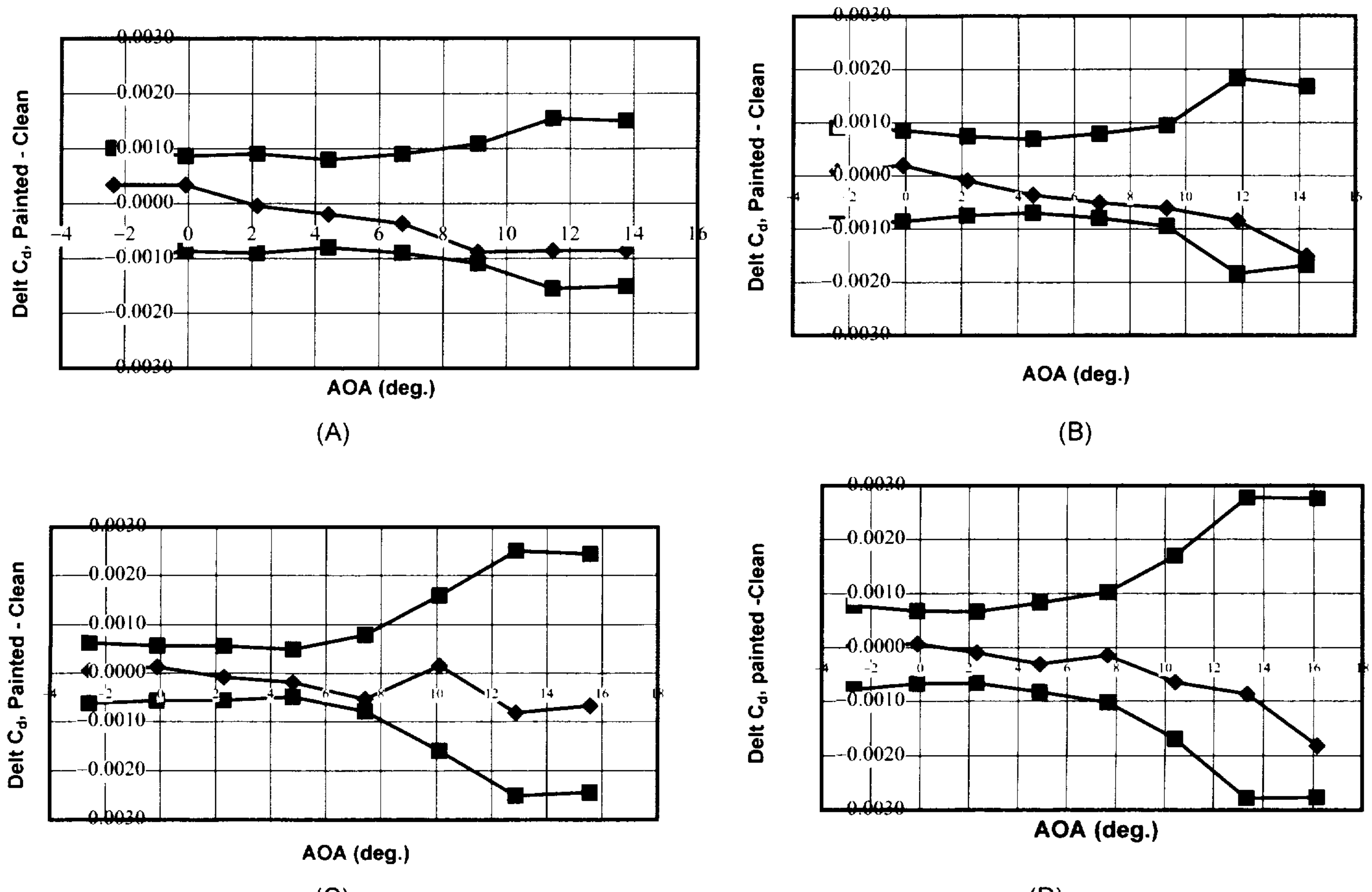


Figure 5. The changes in C_d Vs. AOA at LTPT at Constant Mach= 0.20 and Different Reynolds

A. RE= 4M
B. RE= 6M
C. RE= 11M
D. RE= 13M

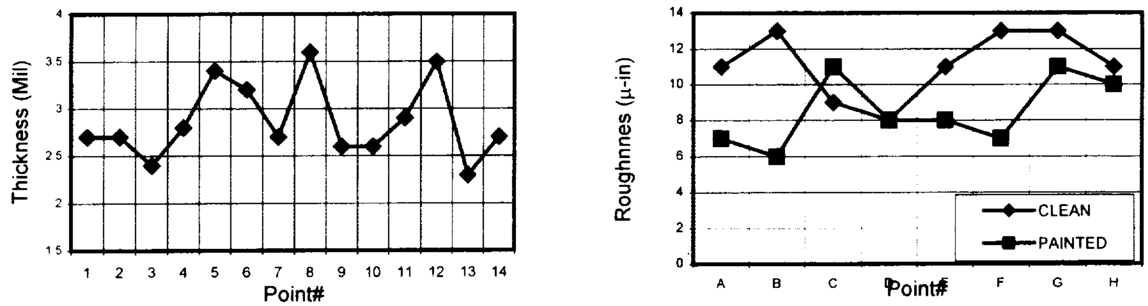


Figure 6. Thickness and Roughness Variations of Painted 65 deg. Delta Wing Model at LTPT

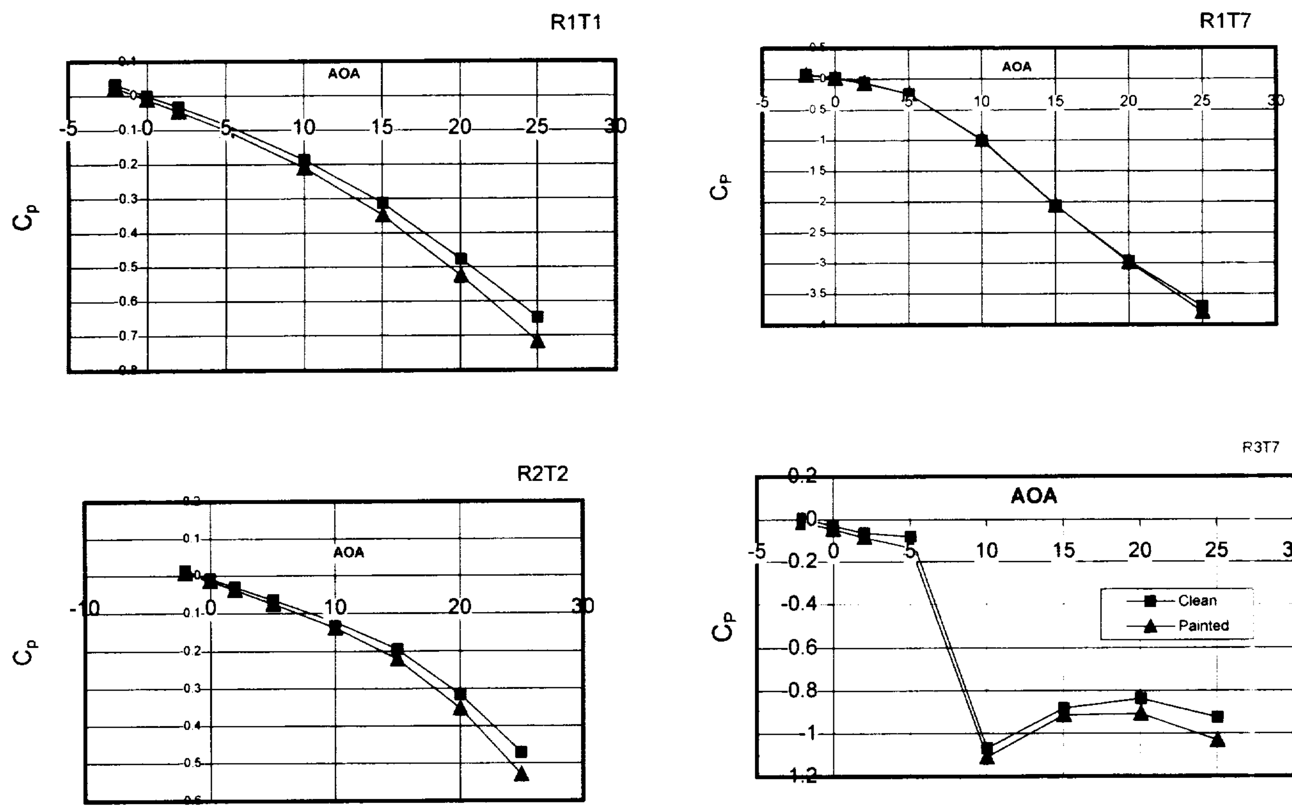


Figure 7. Cp of Painted and Clean Wing Vs. AOA at LTPT at Mach= 0.25, Re= 10M for Selected Taps from Each Steam wise Pressure Rows

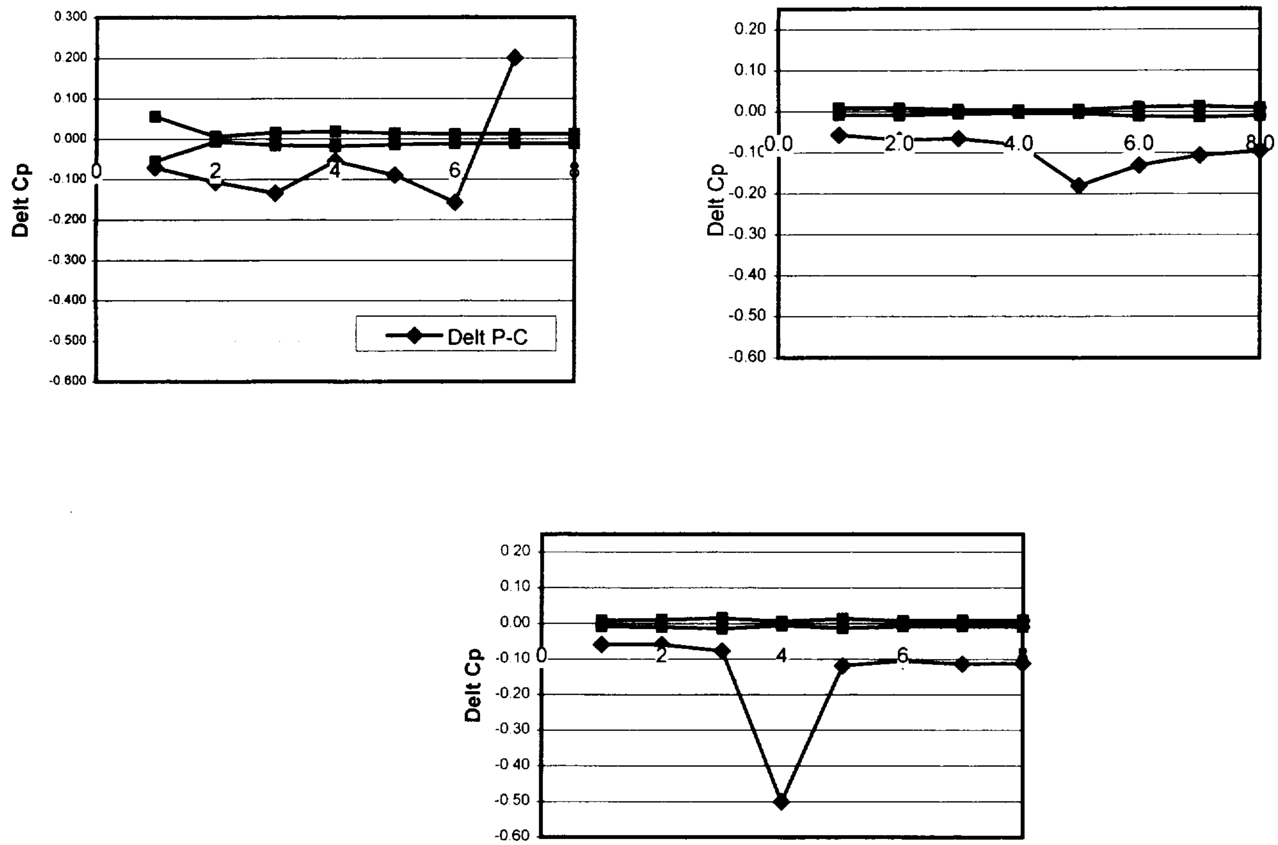


Figure 8. Delta Cp (painted- Clean) as function of AOA of Selected taps at LTPT at M=0.25, Re=5M/ft

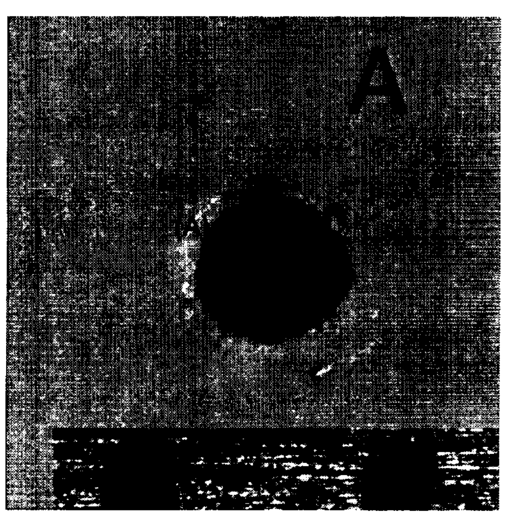
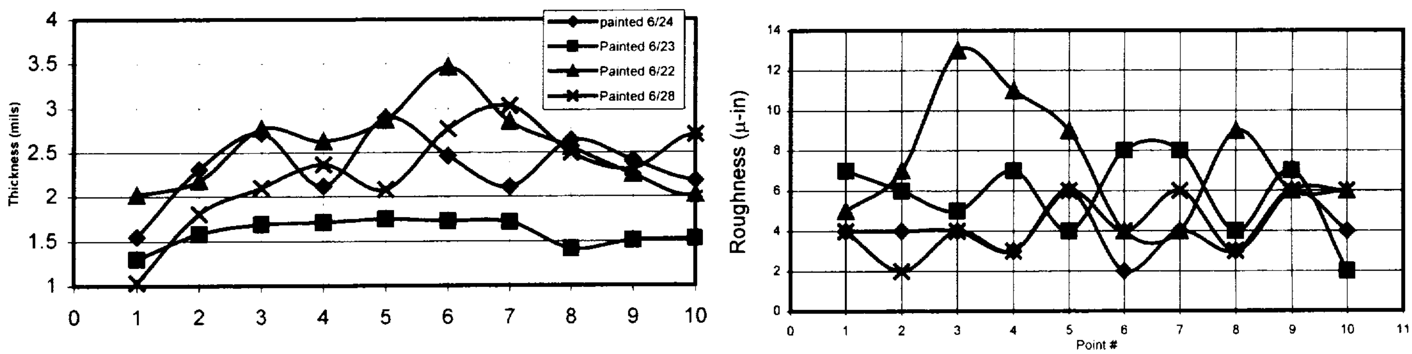


Figure 9. The pressure Taps with PSP paint; A. Clean tap B. Half Clogged



(A) (B)

Figure 10. Thickness and Roughness Variations of Painted Arrow Model at UPWT

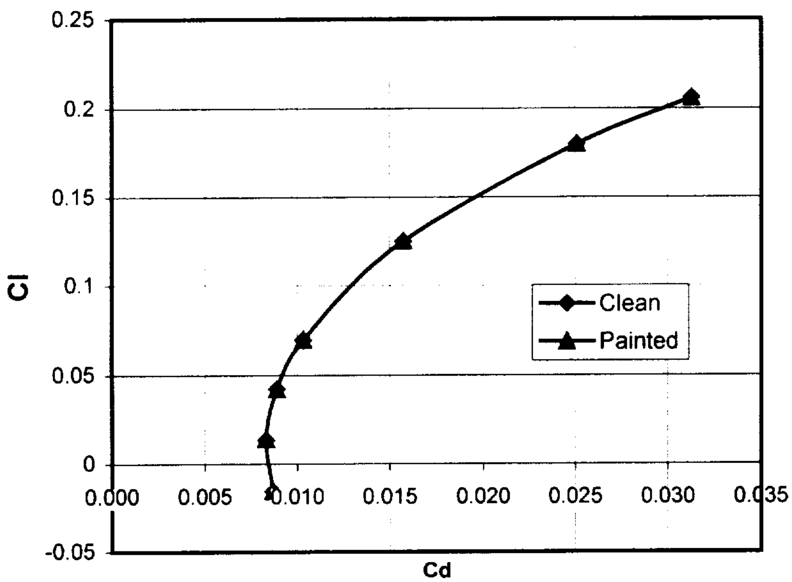


Figure 11. The difference of Cl Vs. Cd of Painted and Clean Wing at UPWT
for Mach= 2.4, Reynolds=XXM for Four Replicates

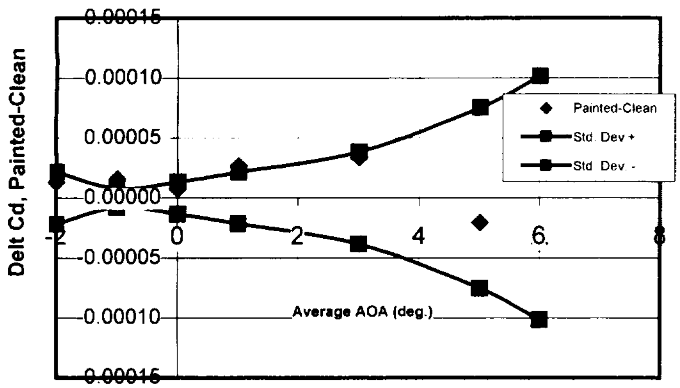


Figure 12. The changes in Cd Vs. AOA at UPWT at Constant Mach= 2.4 and Reynolds = 4M/ft

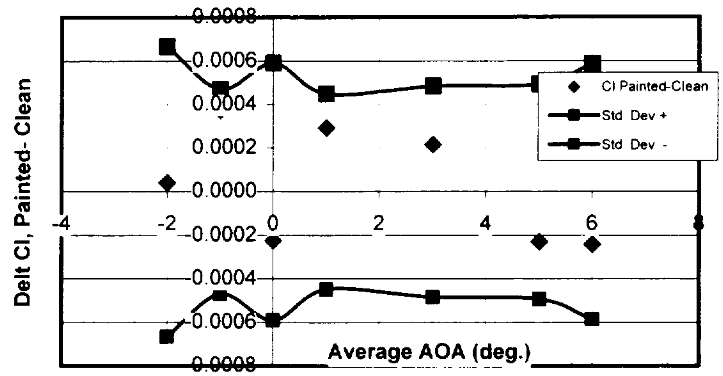


Figure 13. The changes in Cl Vs. AOA at UPWT at Constant Mach= 2.4 and Reynolds = 4M/ft

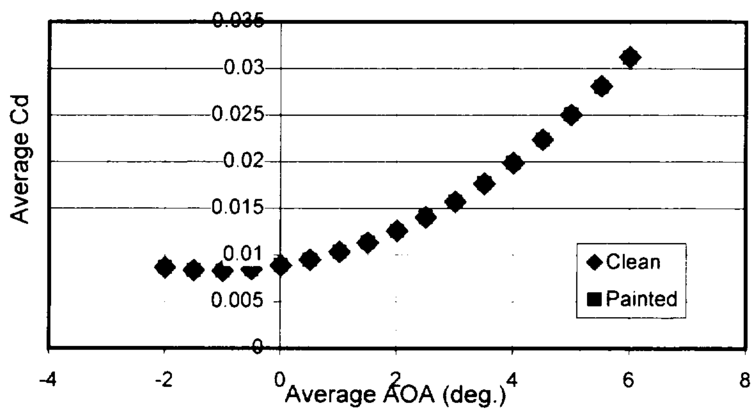


Figure 14. The Average Cd Vs. AOA for Three Conventional Polars at UPWT

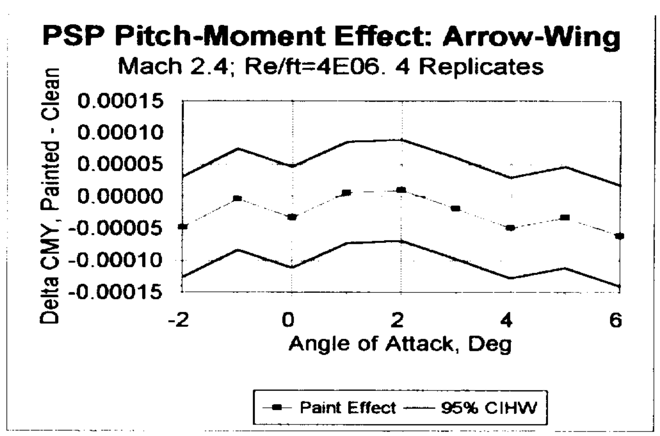


Figure 15. The effect of PSP on the Pitch Moment at UPWT for Four Replicates